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SENSORY RATIO SCALES RELATING HARDNESS AND CRUNCHINESS TO MECHANICAL PROPERTIES OF SPACE CUBES

INTRODUCTION

RECENT DEVELOPMENTS of procedures for direct sensory scaling in psychophysics and psychometrics have demonstrated that equations may be developed to relate texture properties assessed instrumentally to texture properties judged by the human observer (Moskowitz et al., 1972). One particular method, *ratio scaling*, has provided power functions of the form $S = KI^m$, which relates the proportional change in measured mechanical properties (I) to the resultant proportional change of subjectively perceived magnitude (S). The exponent m governs the rate at which perceived intensity increases with physical magnitude. Values of m around 1.5 describe how apparent roughness changes with the measured grit size of sandpaper (Stevens and Harris, 1962) and suggest that since the exponent exceeds 1.0 subjective roughness accelerates with grit size. Small increases in physical roughness are accentuated perceptually. Subjectively estimated hardness, in contrast, obeys a power function whose exponent ranges from 0.6–0.8 (Harper and Stevens, 1964), when the physical correlate is the force/indentation ratio. Subjective hardness decelerates with physical magnitude, so that the perceiver contracts the range of instrumental hardness. Subjectively estimated viscosity and fluidity are governed by power functions with relatively low exponents (0.5; Moskowitz, 1972; Stevens and Guirao, 1964). In order to increase the apparent subjective viscosity of gum or oil liquids by a factor of 10, the physical viscosity must be increased by 100 times.

Power functions provide a useful organizing principle to represent subjective-instrumental relations quantitatively. A large array of texture descriptors has been reported (Szczesniak and Kleyn, 1963; Yoshikawa et al., 1970), and correspondingly large numbers of mechanical properties can be obtained from instruments that measure either one property specifically, or integrate a number of mechanical properties. The number of correlations between a perceptual attribute for texture and a mechanical property is large, and when several mechanical properties are considered in concert the number of potential correlations increases exponentially.

By a judicious representation of the subjective-instrumental relation in terms of a single functional form (power functions, or any other arbitrary function) one may determine the following: (a) what set of power functions (or any other class of function) describe the subjective-instrumental relation; (b) whether substitution of one mechanical property for another alters the exponent of power functions when a single texture attribute is predicted from a number of different mechanical variables; and (c) whether well defined combinations of mechanical properties to yield derived mechanical properties transfer to the subjective realm. Possibility (c) lays the groundwork for a true subjective psychology of texture, existing side-by-side with the physics of texture. Combinations of mechanical properties, in this system, would be reflected by appropriate combinations of their subjective correlates. Only ratio-scaling procedures, however, allow this possibility. Interval (category) scales do not, since ratios of mechanical properties cannot be paralleled by ratios of interval-type sensory measurements.

This study develops one part of a psychophysics of texture that is based upon *functional relations* between subjective attributes and mechanical properties. The work concerns two attributes related to hardness: perceived hardness itself, and crunchiness. Crunchiness, defined operationally for the observers, is the perceived hardness of a food after it is crushed and chewed in the mouth 2–3 times. Although the selection of the best predictor equation can be made by statistical criteria only after a function family (linear, power, exponential, logarithmic, etc.) has been selected to define the subjective-instrumental relation, we arbitrarily selected the power function in view of previous results with the direct scaling of other texture continua. The exponent of a power function is independent both of the multiplicative change of units for a mechanical property and a multiplicative change in the size of numbers selected by the observer (change in modulus for the judgments).

In recent years considerable work has been done with space cubes as part of the NASA program. Space cubes are foods whose size and composition make them excellent model systems for the study of hardness. Hollender (1965) and Klicka et al. (1967) discussed the composition, quality and performance of these foods in detail. The space cubes are sufficiently small and hard so that they can be evaluated for hardness by crushing in the mouth, while simultaneously being tractable for instrumental measurement of mechanical properties.

EXPERIMENTAL

THE STIMULI were four formulations of space cubes (strawberry, graham cracker, sugar cookie and cheese cracker). In the two experiments, the space cubes were withdrawn from storage after 12 months at 4.5°C, and after 16 months at 4.5°C. Properties varied sufficiently with formulation so that the variously flavored space cubes had different hardnesses and crunchiness, sensorially, and were governed by different force/deformation curves. The space cubes were uniform, measuring 1.77 cm on each side. They were thus bite-sized, and easily evaluated by the panelists, as well as ideally sized for instrumental assessment of texture properties.

Mechanical texture properties were measured with the Instron Universal Testing Machine (Floor Model TT-DM), equipped with a load-strain control unit. The cubes were compressed uni-axially under parallel plate conditions until the applied force being displayed on the recorder showed a decrease of 5–10% indicating that rupture had occurred. Compression rates of 0.05, 0.20, 1.00, 2.00 and 5.00 cm/min were used in order to study the effects of this aspect of the test procedure. A compression rate of 5 cm/min was the maximum possible rate that allowed the Instron ¼-sec recorder to respond accurately to the rapidly increasing force. The plate used for compression had a surface area greater than that of the samples. Ideally, this means that all parts of the cube were subjected to the same strain. In actuality, however, rough areas, uneven surfaces and non-parallel faces all produced deviations from the ideal compression, thus causing scatter in the obtained measurements. Ten replications were made at each instrumental test condition as a minimum for statistical analysis.

From the force-deformation curve the following properties were calculated:

(1) **Apparent modulus of elasticity**–(the ratio of stress to strain along the linear portion of the loading curve; it may be a useful measure of the stiffness or rigidity of the sample).
(2) **Ultimate strength**–(the stress at rupture; a possible correlate of hardness).

Subjective assessment of texture properties

Two separate experiments were conducted in order to evaluate the mechanical properties related to subjective hardness. In Experiment I, 48 panelists evaluated both the hardness and the crunchiness of three flavors of space cubes (strawberry, graham cracker and sugar cookie)

Table 1—Sensory-Instrumental Functions

(1)	log Hardness = 0.41 log Modulus of elasticity	+ 0.61 (r = 0.80)
(2)	log Hardness = 0.61 log Ultimate strength	+ 1.02 (r = 0.75)
(3)	log Crunchiness = 0.55 log Mod. of elasticity	− 0.05 (r = 0.89)
(4)	log Crunchiness = 0.72 log Ultimate strength	+ 0.61 (r = 0.74)
(5)[a]	log Crunchiness = 1.22 log Hardness	− 0.62 (r = 0.93)
(6)[a]	log Ultimate strength = 0.65 log Mod. elasticity	− 0.58 (r = 0.93)

[a] Represents the average regression function when it is computed with each variable serving as the criterion

after a storage period of 12 months. In Experiment II, 30 panelists (18 from Experiment I, 12 new panelists) estimated the 'first hardness' (corresponding to hardness in Experiment I) and the 'second hardness' (corresponding to crunchiness) of four flavors of space cubes withdrawn from storage after 16 months.

The sealed cans containing the space cubes were withdrawn from storage and allowed to equilibrate at room temperature for about 24 hr prior to the test. The sealed cans were opened on the test day, and immediately thereafter the cubes were transferred to quart-sized jars, (wide mouthed, Mason) with desiccant packets at the bottom. The desiccant maintained the dryness of the space cubes, and prevented the cubes from picking up moisture that could alter their mechanical properties.

For purposes of standardizing both the texture descriptors and the sampling method, the panelists were presented with the following definitions and procedures:

(1) Hardness—the amount of force exerted by the molar teeth needed to crack the cube in the mouth (first bite); and
(2) Crunchiness—the amount of force necessary to crush and grind the cube during the second and subsequent chews.

The panelists were provided with the following instructions, and told to perform exactly according to the procedure outlined.

(1) Put the largest granule (soy protein chip) into your mouth between your *molar teeth* (you may use either side of your mouth).
(2) Bite down gradually until the granule breaks—the force required to do this is *hardness*.
(3) Continue to chew two or three times to get an idea of the amount of force needed to crush and grind the material. This overall force is *crunchiness*.

The panelists were instructed in the use of ratio scaling procedures [specifically the method of magnitude estimation (Moskowitz, 1970; Moskowitz and Sidel, 1971)]. Their two numerical estimates were to reflect ratios of hardness or crunchiness, respectively. In both experiments irregularly shaped soy protein chips were used as standards to anchor the judgments. In both experiments care was taken to make the magnitude estimates of both hardness and crunchiness comparable, both across stimuli, and comparable to each other. For example, a rating of 300 on hardness and 100 on crunchiness indicates that the impression of hardness is three times as great as the impression of crunchiness.

The geometric mean of the magnitude estimates was computed for each space cube, and for each attribute. A regression analysis was used in order to find the best-fitting parameters (k, m) of a simple power function $S = kI^m$, relating sensory judgment S to mechanical property I. The geometric mean is the preferred measure of central tendency for magnitude estimates since they distribute log-normally, and a power function is the preferred functional form for subjective-instrumental relations derived from magnitude estimation.

RESULTS

TABLE 1 presents the functions that relate both hardness and crunchiness to the modulus of elasticity at 5 cm/min compression rate, and to the ultimate strength at 5 cm/min. Note that the data from the two experiments have been pooled to yield estimates for seven different cubes. Figure 1 also shows the best-fitting power functions relating the mean magnitude estimate to the two physical continua.

The present results suggest that both hardness and crunchiness are governed, as a first approximation, by simple power functions, although some departures from the function yield scatter about the best fitting regression line. The exponent for hardness is approximately 0.4 when the independent physical continuum is the modulus of elasticity, and 0.6 when hardness is a function of the ultimate strength. Thus, hardness grows less rapidly than the mechanically measured texture attribute against which it is correlated. Crunchiness shows a similar decelerating function, and its exponent is 0.5 as a function of the modulus of elasticity, and 0.7 as a function of the ultimate strength (Table 1). Subjectively, a tenfold increase in the measured mechanical property is perceived only as a three- to fivefold increase in hardness and in crunchiness. The tactile and kinesthetic systems that respond to mechanical properties and transform these to information about texture tend to compress the range of physical variation. The range of hardness impressions on the subjective side is considerably smaller than what would be expected were the sensory system to map veridically the physical properties into the subjective realm. Large changes in the force-deformation curve may yield only minor perceptual changes.

From simple psychophysical measurement one may deduce only the form of the intensity function for texture, but not necessarily conclude which of many potential physical continua is most responsible for producing that texture attribute. Here, two continua correlate with impressions of hardness and crunchiness. They are correlated with each other

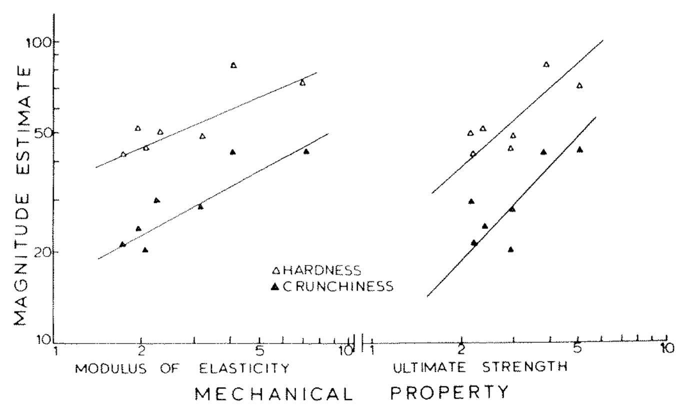

Fig. 1—Relation between the geometric mean of subjective magnitude estimation (both of hardness and of crunchiness) and the mechanical properties of the modulus of elasticity and the ultimate strength. Both mechanical properties were measured by the Instron Universal Testing Machine at a compression speed of 5 cm/min. The subjective-instrumental functions are plotted in log-log coordinates, in which power functions ($S = kI^m$, S = sensory property, I = mechanical property) show up as straight lines. The exponents of best-fitting power functions are always less than 1.0. The dimensions of both mechanical properties are kg/cm², and the abscissa numbers for the modulus of elasticity and for the ultimate strength must be multiplied by 200 and 5, respectively.

(Table 1), and the regression function relating them allows the investigator to predict the modulus of elasticity from the ultimate strength and vice versa. There are also two possibilities for determining which physical correlate is maximally responsible for the subjective texture impression. One is the degree of correlation, or the statistical criterion of best-fit. By that criterion the modulus of elasticity at 5 cm/min shows the higher correlation coefficient, and is thus more strongly related both to hardness and to crunchiness. The other possibility is the size of the exponents. One can argue that exponents closer to 1.0 represent a veridical subjective-instrumental function. As the exponent either increases or decreases from 1.0 subjective ratios of texture magnitudes gradually diverge from instrumentally measured ratios. Ideally, therefore, in a study of human texture perception the investigator should determine which of his subjective-instrumental functions are most veridical. According to this criterion of veridicality the mechanical property of ultimate strength is more appropriate, since its exponents for both hardness and crunchiness exceeded those obtained with the modulus of elasticity.

DISCUSSION

EQUATIONS relating subjective to instrumental texture measures have at least two important applications. On one hand, they illustrate how ratios of mechanical properties may be transformed to ratios of perceived texture magnitude. A psychophysics of texture may be developed, with predictor equations that parallel formulae in physics by a collection of a representative set of exponents relating mechanical to subjective attributes. This application constitutes an approach to texture based upon functional relations between two receptor systems, the physical instrument and the evaluating observer.

The second application is that of quality control. Continual instrumental monitoring of processes whose end products are foods with desired texture can yield only measures of physical magnitudes read by an instrument. These physical measures reflect shifts from the ideal values of mechanical properties desired in the product, but do not indicate whether large shifts in mechanical properties correspond to important, to moderate or perhaps even to only minor changes in the subjective texture attribute correlated with the measure. By means of appropriate instrumental-subjective equations one may effectively rescale the process monitoring instrument to read directly the texture magnitude that would be obtained from subjective evaluation. In the estimation of hardness, for example, the output of a continual monitor of the modulus of elasticity could be transformed to read directly in terms of subjective hardness (i.e., by raising the instrumental reading to the 0.4 power). Appropriate implementation of quality control, therefore, could be effected with respect to subjective limits, and the process monitor would respond *as if* it were a panel of human judges.

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